

In conclusion, it was shown that densely packed monolithic linear arrays of strip buried heterostructure lasers exhibited similar characteristics as single-SBH lasers with much higher output power. The spectral behavior of the arrays also indicated that there is some field interaction between the neighboring lasers, though this may not be strong enough to completely synchronize the array probably because of the slight material inhomogeneity present. The high output power provided by the array should be useful as a high-power optical source, which when converted back to electrical energy could be used for powering electronic circuits. The high degree of uniformity in laser characteristics of the lasers in the arrays is important when they are used as

high-density active multiplexers in optical-fiber communication.

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Silicon implantation in GaAs

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The electrical properties of room-temperature Si implants in GaAs have been studied. The implantations were done at 300 keV with doses ranging from 1.7×10^{13} to 1.7×10^{15} cm⁻². The implanted samples were annealed with silicon nitride encapsulants in H₂ atmosphere for 30 min at temperatures ranging from 800 to 900°C to electrically activate the implanted ions. Results show that the implanted layers are *n* type, which implies that the Si ions preferentially go into Ga sites substitutionally. For low-dose implants, high (~90%) electrical activation of the implanted ions is achieved and the depth distribution of the free-electron concentration in the implanted layer roughly follows a Gaussian. However, for high-dose implants, the activation is poor (<15% for a 900°C anneal) and the electron concentration profile is flat and deeper than the expected range.

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The desire to fabricate fast (microwave) devices has generated considerable interest over the last few years in the production of controlled reproducible *n*-type layers in GaAs by ion implantation.¹⁻³ Although both room temperature and hot (150–350 °C) implants of S, Se, and Te have been used successfully¹⁻³ to produce *n*-type layers with electron concentrations of $\sim 10^{17}$ cm⁻³ (e.g., for a typical FET application), one finds that to reach high electron concentrations ($\geq 10^{18}$ cm⁻³ for good Ohmic contacts) hot implants are necessary.^{1,2} Hot implants are, however, inconvenient from the practical point of view especially if they have to be performed at a later stage in a device-fabrication process. There have been recent indications^{4,5} that one can achieve high electrical activation of Si implanted at room temperature. In

this letter we report on the electrical properties of room-temperature Si implants in GaAs where good electrical activity, at least for low doses ($\leq 1.7 \times 10^{14}$ cm⁻²), is confirmed. In some cases, electron-concentration *n*-vs.-depth *d* measurements indicate values of $n > 10^{18}$ cm⁻³.

Si was implanted at room temperature in <100> semi-insulating (Cr-doped) GaAs with the beam incident at an angle of approximately 10° from the normal to the sample surface in order to minimize channeling. The energy of implantation was 300 keV, and the dose range chosen was from 1.7×10^{13} to 1.7×10^{15} cm⁻². All samples were subsequently annealed for 30 min in H₂ at 800, 850 or 900 °C after being coated with ~ 2000 Å of reactively sputtered silicon nitride. The silicon nitride films adhered well during annealing. After annealing, the silicon nitride films were removed with HF, and Au-Ge/Pt dots were evaporated through mechanical masks to provide electrical contacts. The contacts were

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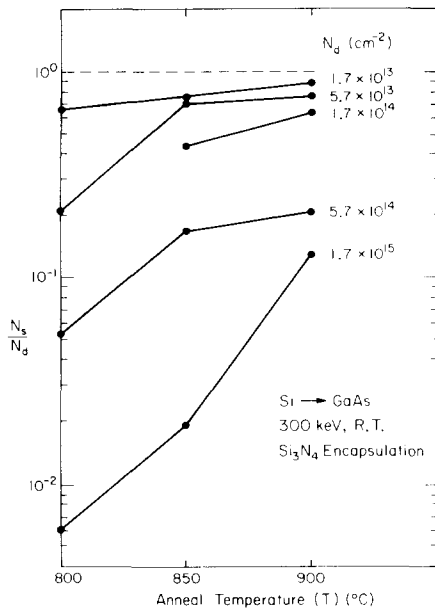


FIG. 1. The ratio of the effective sheet electron concentration to the implantation dose (N_s/N_d) versus anneal temperature T with N_d as a parameter.

alloyed at 450 °C for approximately 2 min. Van der Pauw mesas were then etched for differential Hall-effect measurements of the stripping type, described elsewhere.⁶

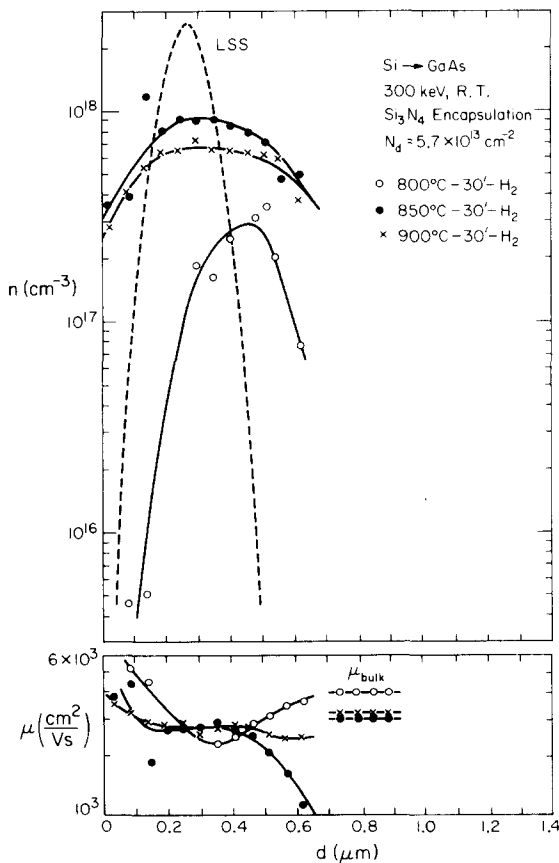


FIG. 2. Electron concentration n and mobility μ versus depth d . The profiles are for three samples implanted with the same dose, $N_d = 5.74 \times 10^{13} \text{ cm}^{-2}$ and annealed at three different temperatures. The μ_{bulk} values are estimated for the peak values of n in the electron concentration profiles (Ref. 11).

The dependence of the ratio of the effective sheet electron concentration⁷ to the implantation dose (N_s/N_d) on the anneal temperature T with N_d as a parameter is shown in Fig. 1. For low doses, N_s/N_d is found to approach unity. The highest dopant activity of about 90% is obtained for the sample implanted with $N_d = 1.7 \times 10^{13} \text{ cm}^{-2}$ and annealed at 900 °C for 30 min. Samples implanted with the higher doses show considerably lower values of N_s/N_d for the same anneal temperature. This may be because the higher implantation doses result in (a) increased damage which cannot be annealed fully at the same temperature, (b) higher incorporation of Si atoms in As sites producing increased compensation, and (c) increased formation of $\text{Si}_{\text{Ga}}\text{-Si}_{\text{As}}$ neutral neighbor pairs.⁸ The functional dependence of N_s/N_d on T follows a similar trend for all doses except for the highest one, for which it is quite different. We speculate that this may be so because at a dose of $\sim 1 \times 10^{15} \text{ cm}^{-2}$ the implanted layer may be more nearly amorphous than single crystalline, so that different annealing mechanisms may be operative in the temperature range 800–900 °C.

In Fig. 2, electron concentration n and mobility μ depth profiles are shown for three samples implanted with the same dose, $N_d = 5.7 \times 10^{13} \text{ cm}^{-2}$, and annealed at three different temperatures. The Si concentration profile calculated using LSS range parameters and a Gaussian approximation^{9,10} is also plotted for comparison. For the samples annealed at 850 and 900 °C, the electron concentration profiles are roughly Gaussian with their maximum located approximately at the depth predicted by the LSS theory. The difference in the two profiles should be considered insignificant and within measurement and computational errors. The broadening of the profiles, as compared to the LSS profile,

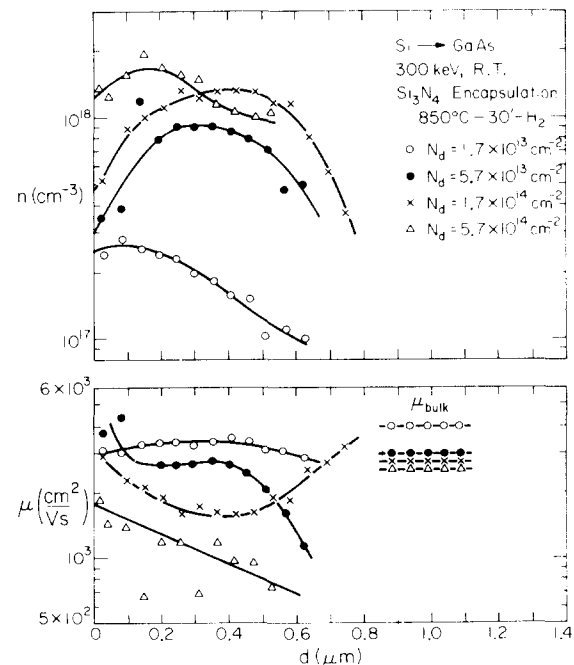


FIG. 3. Electron concentration n and mobility μ versus depth d . The profiles are for four samples implanted with four different doses, but annealed at the same temperature, 850 °C. The μ_{bulk} values are estimated as in Fig. 2.

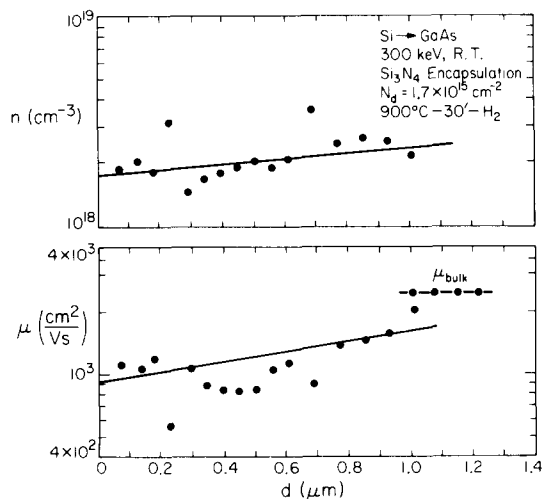


FIG. 4. Electron concentration n and mobility μ versus depth d . The profiles are for a sample implanted with $N_d = 1.74 \times 10^{15} \text{ cm}^{-2}$ and annealed at 900°C . The μ_{bulk} value is estimated as in Fig. 2.

may be due to diffusion. The electron concentration profile for the sample annealed at 800°C indicates that a temperature of 800°C is not high enough to fully activate the implanted Si. The mobility profiles for the three samples show that the values of mobility are all within a factor of 2. The values of μ are somewhat lower than the values of μ in bulk GaAs¹¹ for electron concentrations equal to the measured peak electron concentrations.

The effect of the dose N_d on the profiles of n and μ is shown in Fig. 3, for samples which were all annealed at 850°C . It is interesting to note that, although one achieves higher values of n with higher N_d , the increase in n is much smaller than the increase in N_d (an increase in N_d by a factor of 33 produces an increase in the peak value of n by only a factor of 6). This indicates that higher values of N_d may not necessarily produce higher values of n . The shifting of the electron concentration profiles toward the surface for $N_d = 1.7 \times 10^{13} \text{ cm}^{-2}$ and also for $N_d = 5.7 \times 10^{14} \text{ cm}^{-2}$ cannot be explained by a simple argument. More experiments are needed to confirm this observation. The mobility profiles depicted in Fig. 3 show that the value of mobility decreases systematically with increasing dose (electron concentration), a result also found in bulk GaAs.¹¹ However, the decrease in the mobility appears to be greater than the decrease in the bulk mobility for the same range of the peak doping concentrations.¹¹

The different behavior of $1.7 \times 10^{15} \text{ cm}^{-2}$ implants shown in Fig. 1 is further illustrated in Fig. 4 where the

profiles of n and μ are shown for the sample annealed at 900°C . The carrier concentration profile is not only deep but also flat. This result suggests that for high doses ($\geq 10^{15} \text{ cm}^{-2}$) the distribution of the donor ions after annealing is qualitatively different from the distributions found for lower doses. A possible explanation could be that there is a damage threshold beyond which the diffusion of the Si ions is considerably enhanced and modified. It should be interesting to investigate this effect further.

In conclusion, the following statements can be made about the room-temperature Si implants in GaAs:

(a) For low doses ($N_d \leq 1.7 \times 10^{14} \text{ cm}^{-2}$) one achieves good electrical activation ($> 50\%$) of the implanted Si ions when the layers are annealed at 900°C for 30 min in H_2 with a silicon nitride cap.

(b) Higher doses do not necessarily yield higher values of electron concentration. The highest doping concentration attained is $\sim 2 \times 10^{18} \text{ cm}^{-3}$.

(c) The depth profiles of the electron concentration for $N_d \leq 5.7 \times 10^{14} \text{ cm}^{-2}$ are roughly Gaussian. However, for $N_d = 1.7 \times 10^{15} \text{ cm}^{-2}$ and 900°C annealing, the profile is flat.

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